DONuT Cross Section Reference

Abstract: Compilation of formulae and numbers from which the cross section results are derived.

1 Relative Cross Sections

1.1 CCτ / CCe

The CCτ to CCe cross section is the "cleanest" result, more straightforward to calculate than the muon measurement. It is given as

$$\frac{\sigma_\tau^{\text{const}}}{\sigma_e^{\text{const}}} = \frac{N_\tau^{\text{obs}}}{N_e^{\text{obs}}} \cdot \frac{\left(f\sum EKTt\right)_e}{\left(f\sum EKTt\right)_\tau} \cdot \frac{F_e}{F_\tau} \cdot \frac{\varepsilon_e}{\varepsilon_\tau} \qquad (1)$$

The terms are defined in the memo "Estimated Number of Interactions" 2 March 2007. Some of the efficiencies such as stripping, scanning and location largely cancel. It is difficult to determine if these efficiencies are different for types of neutrino interactions. We will assume that any systematic difference in scan efficiency is less than the assigned uncertainty on this efficiency, $\varepsilon_{\text{scan}} = 0.865 \pm 0.066$. The ratio of the trigger efficiencies is taken into account with the MC analysis, in the sums, but the ratio of electron to tau trigger efficiencies is 1.02, a very small effect.

For the number of observed tau interactions, we believe the most accurate result is the multivariate analysis. Summing the tau probabilities for the nine events yields 7.52 events. This result is automatically background-subtracted.

For the number of electron neutrino interactions we use Baller's analysis of 21 March 2007, with a cut of $E_e > 20$ GeV. The number of events is 113. The efficiency is 0.561. His analysis also estimates a background of NC feed-through events, at a level of 0.164. Therefore we use the corrected value

$$N_e^{\text{obs}} = N_e - N_{\text{bkg}} = 113 \times (1 - 0.164) = 94.5 \qquad (2)$$

together with ε=0.561.

The part of the tau efficiency that does cancel is the secondary vertex location efficiency, estimated by Furukawa to be 0.51. There is also a requirement that the primary vertex not be in the first (downstream) 8 plates. There are 61 events located in the first 8 plates, so an estimate of the secondary vertex efficiency is 0.51×(1- 61/578) = 0.46.

Inserting numbers into (1) gives

$$\frac{\sigma_\tau^{\text{const}}}{\sigma_e^{\text{const}}} = \frac{7.5}{94.5} \cdot \frac{4.62}{2.54} \cdot \frac{68.7}{10.6} \cdot \frac{0.561}{0.46} = 1.14 \qquad (3)$$

1.1.1 Uncertainty in CCτ / CCe

The uncertainties are statistical and systematic. In this ratio result, the systematic uncertainty is expected to be small compared to the statistical error. The statistical error is given simply as

$$\delta\left(\frac{\sigma_\tau}{\sigma_e}\right)=\left\{\left(\frac{\delta N_\tau}{N_\tau}\right)\oplus\left(\frac{\delta N_e}{N_e}\right)\right\}\cdot\frac{\sigma_\tau}{\sigma_e}=\left\{\left(\frac{1}{7.52}\right)+\left(\frac{1}{113}\right)\right\}^{\frac{1}{2}}\cdot 1.05=0.40$$

A systematic uncertainty indicates that some efficiencies do not cancel in the ratio. There are two quantities that are possibly significant. First, as mentioned, we don't know if the scanning was equally efficient for electrons and taus. It cannot be any larger than 6% and probably much less. Second, when the charm production parameter *n* is varied from 6.0 to 8.8, the kinematic effect on interactions within the emulsion are not quite the same in electron or tau neutrinos. MC results show that this ratio in the second term on the rhs of (1) may change by 15%. Therefore, we can be confident that there are no systematic uncertainties in the cross section ratio result that exceed 20%. We assign a systematic error of 0.21.

1.2 CCτ / CCμ

The tau to muon cross section analysis follows the tau to electron analysis, except that the background in the muon signal is other muon events, the non-prompt events. Another backgound comes from NC interactions (or CC*e* for that matter) in which a π decays in-flight to a muon. MC studies indicate (from Baller) that the rate of this process, where a decay-in-flight is tagged as a muon in a NC events, is 4×10^{-3}, or 0.9 events (212*0.004).

The non-prompt fraction is taken to be 0.39±0.05. Thus the total estimated ν_μ CC interactions is 227×0.61 = 138±20, where both the error in number ($\sqrt{138} \oplus (0.08/0.61)$) and error in prompt fraction is computed.

The cross section ratio is thus

$$\frac{\sigma_\tau^{\text{const}}}{\sigma_\mu^{\text{const}}}=\frac{7.5}{138}\cdot\frac{4.33}{2.54}\cdot\frac{64.6}{10.6}\cdot\frac{1}{0.46}=1.23 \tag{5}$$

1.2.1 Uncertainty in CCτ / CCμ

From the above numbers

$$\delta\left(\frac{\sigma_\tau}{\sigma_\mu}\right)=\left\{\left(\frac{\delta N_\tau}{N_\tau}\right)\oplus\left(\frac{\delta N_\mu}{N_\mu}\right)\right\}\cdot\frac{\sigma_\tau}{\sigma_e}=\left\{\left(\frac{1}{7.52}\right)+\left(\frac{20}{138}\right)^2\right\}^{\frac{1}{2}}\cdot 0.92=0.36$$

The systematic uncertainty estimate follows from the estimate for electron-neutrino interactions, 15%, which gives ±0.14.

2 Absolute Cross Section

2.1 CCτ

In the absolute ν_τ CC cross section measurement, all the analysis efficiencies need to be included. The total product (assumed to be uncorrelated) is

$$\varepsilon_{\text{TOT}}=\varepsilon_{\text{strip}}\cdot\varepsilon_{\text{scan}}\cdot\varepsilon_{\text{trig}}\cdot\varepsilon_{\text{loc}}\cdot\varepsilon_{\text{vtx}} \tag{7}$$

The stripping efficiency is taken to be 0.98. The eye-scan efficiency is 0.865±0.66. The trigger efficiency, a beam-weighted average over the four periods times live-time and self-veto

$$\varepsilon_{\text{trig}}=\varepsilon_{\text{counter}}\cdot\varepsilon_{\text{self-veto}}\cdot\varepsilon_{\text{live}}=(0.961)\cdot(0.96)\cdot(0.89)=0.82 \tag{8}$$

The location efficiency is taken to be 0.66. And the secondary vertex finding efficiency is estimated to be 0.49. The product (7) becomes

$$\varepsilon_{\mathrm{TOT}} = (0.98)\cdot(0.865)\cdot(0.82)\cdot(0.66)\cdot(0.46) = 0.21 \tag{9}$$

The absolute cross section becomes

$$\sigma_\tau^{\mathrm{const}} = \frac{N_\tau^{\mathrm{obs}}\cdot 0.505\times10^{-38}\,\mathrm{cm}^2}{\varepsilon_{\mathrm{TOT}}\cdot F_\tau\cdot f\left\langle\sum EKT\right\rangle} = \frac{7.5\cdot 0.505\times10^{-38}}{(0.21)\cdot(10.6)\cdot(2.54)} = 1.33\cdot\left\langle\sigma_e^{\mathrm{const}}\right\rangle$$

$$\sigma_\tau^{\mathrm{const}} = 0.67\times10^{-38}\ \mathrm{cm}^2 \tag{10}$$

The explicit factor of 0.5×10^{-38} appears only because it is explicitly part of the constant term *F*.

2.1.1 Uncertainty in Absolute Cross Section

The relative statistical error is simply $(\sqrt{7.5})^{-1} = 0.37$.

The relative systematic uncertainty in the charm cross section and branching ratios is 0.23.

The relative systematic uncertainty due to the differential charm production (the n value) is 0.39 as given as the ratio of $f\langle\Sigma\rangle$ for tau at $n = 7.4$ to $n = 8.8$.